LE-7Aエンジン液体水素インデューサの性能向上設計に関する研究

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論 文 内 容 要 旨

The H-IIA launch vehicle, Japan's present expendable launch vehicle, which will be capable of carrying a 4-ton-class payload into a geostationary transfer orbit, has been under development since 1995. The LE-7A engine, which is used in the first stage of the H-IIA rocket, provides a thrust of 1,100 kN using liquid oxygen and liquid hydrogen as propellants. This engine, an improved version of the LE-7 engine that was used in the H-II launch vehicle, was designed to increase reliability by simplifying the engine system and reducing the number of engine components, which also results in a decrease in manufacturing costs.

The LE-7A fuel turbopump (FTP) was also developed to decrease manufacturing costs, as well as to achieve higher reliability utilizing experience gained in the development of the LE-7 FTP. This turbopump has two centrifugal impellers and a single inducer, which is required for high durability and stable operation under all operating conditions during flight.

In the LE-7A engine tests, the original inducer of the LE-7A FTP showed good suction performance at a flow rate higher than that of the nominal operation, which is lower than that of the design. The change of this operating condition was made to complete the engine system. However, it was clarified that the inducer did not achieve the required suction performance at a flow rate lower than that of the nominal operation and that the inducer also showed rotating cavitation. Furthermore, the inducer showed sudden remarkable head deterioration near the required net positive suction head (NPSH) based on the design specifications. Simultaneously, unacceptable rotor vibrations occurred. This degradation of inducer suction performance was caused by a rotating-stall-type phenomenon, which is closely related to backflow cavitation at the inducer inlet. Excessive backflow cavitation produced by the insufficiency of the inlet flow coefficient is considered to obstruct the flowfield around the inducer inlet, which results in an unstable head capacity curve at the constant inlet pressure. The rotating speed of this phenomenon is less than that of the rotating blades, which showed definite difference from rotating cavitation. The rotating speed of rotating cavitation is higher than that of the rotating blades.

A program to develop an alternate inducer was commenced in October 2000 to improve the flow characteristics of the inducer inlet and to suppress rotating cavitation. To suppress the excessive backflow, the inlet flow coefficient was increased by reducing the tip diameter of the inducer inlet, which resulted in a decrease of the flow incidence angle compared with that of the original inducer. Testing of the FTP with the alternate inducer was performed using both liquid hydrogen and also water as test fluids. In the water tests, visual observations of the flowfield were performed and data for the inducer's structural integrity were obtained by measuring the strain on the inducer blades using strain gauges placed on the surface of the blades.

Detailed data on the alternate inducer were obtained during the tests of the LE-7A liquid hydrogen turbopump alone. In these tests, the turbopump was connected with the hydrogen feed-line which has the same configuration as that used in an actual flight. The tests were conducted under various conditions, including flow rate (Q/Qd), rotational speed, and inducer inlet pressure, taking the flight operating conditions into consideration.

Besides measuring the hydraulic and mechanical performance in the steady state, various dynamic properties, including pressure fluctuations just around the inducer, shaft vibrations, and accelerations, were measured. Pressure fluctuations were measured upstream, just around the blade tip and downstream of the inducer by quartz-type wideband oscillating pressure sensors.

As of April 2002, seven liquid hydrogen turbopumps with alternate inducers were demonstrated to operate successfully at the low NPSH. In hot firing tests of the LE-7A engines, the hydrogen turbopumps were verified to have sufficient durability and suction performance. The sudden drop of head that appeared in the original inducer near the required NPSH did not appear at all, even when the inlet flow coefficient =0.076, was less than the design flow coefficient =0.08. In the present case, rotating cavitation was also perfectly suppressed by the installation of an oblique step under all operating conditions in the hydrogen tests, but could not be completely suppressed in the water test even using the same oblique step at the same flow coefficient, mentioned later. It is believed that hydrogen is more effective than any other fluids in suppressing rotating cavitation due to its thermodynamic properties and its large compressibility which has the same effect as cavitation compliance on suppression of rotating cavitation.

The alternate inducer was also tested at a rotational speed of 7,500 rpm using a closed-loop inducer test facility at the Kakuda Propulsion Laboratory (KPL) of the National Aerospace Laboratory (NAL). The working fluid was degasified water at room temperature and visual observations were performed using a casing made of a transparent plastic. From visual observations of the water tests, it was verified that the backflow cavitation of the inducer inlet with the alternate inducer was greatly weakened compare with that of the original inducer when both the inducers were compared at the nominal flow coefficient. Rotating cavitation was not completely suppressed in these tests. Data on static and dynamic strain of the inducer blades and pressure fluctuations were also acquired in the water tests. An evaluation of the structural design of the alternate inducer was performed by finite element method analysis of a three-dimensional solid model using pressure profiles obtained by computational fluid dynamics. Evaluation of fatigue of the alternate inducer was also conducted using the stress which was estimated from the results of water tests.

The large radial displacements with a frequency of around 350 H_z, which appeared in the turbopump with the original inducer, were completely suppressed in the turbopump with the alternate inducer. Therefore, it can be concluded that the design of the alternate inducer is appropriate. However, we cannot fully explain the detailed mechanism of the relationship between the sudden drop of head and the strong backflow in the inlet of the original inducer. In water tests, the original inducer did not show the sudden head degradation which produced the rotating-stall-type phenomenon that was observed in the liquid hydrogen tests.

The second H-IIA test flight vehicle, in which the LE-7A FTP with the alternate inducer was installed, was successfully launched in February 2002 from the NASDA (JAXA at present) Tanegashima Space Center and the LE-7A engine operated perfectly. Since then, the third (on September 10, 2002), fourth (on December 14, 2002), and fifth flights (on March 28, 2003) have successful. Many flight data concerning the LE-7A FTP have been obtained and analyzed. The rotational speed, inducer inlet pressure, inlet temperature, inducer discharge pressure, bearing temperature, etc., were acquired during the actual flights using measurement apparatuses with high sampling speed. Since data of flow rate, rotor vibration and turbopump acceleration, etc., were not directly obtained, they were estimated using other measured data. The operating conditions of the FTP, such as the inducer inlet pressure and inlet temperature, ware, of course, changed momently during the flight. The measured data of pressures and temperatures at the various portions of the LE-7A engine are highly stable, which show that both the turbopumps are operated perfectly throughout flight. The cavitation number K gradually decreased from the ignition of the LE-7A engine to around 100 sec after engine start-up, because the LH_2 tank pressure was appropriately controlled taking the change of atmospheric pressure into account. After that time, the LH_2 tank pressure was also continuously controlled within the range which was set in advance. The wholly progressive decrease of cavitation number resulted from the gradual increase of inducer inlet temperature due to the heat transfer from the heat insulation materials into the LH_2 tank and propellant feed-line. The cavitation number had reached a minimum value of $K \fallingdotseq 0.035$, when the LE-7A engine was shut down. The inducer pressure rise coefficient was, however, constantly stable in spite of the change of cavitation number throughout the flight.

論文審査結果の要旨

ロケットエンジン用インデューサは、キャビテーションを発生した状態で使用するため、最近の液体ロケットエンジンの大型・大流量・高圧化にともなって、キャビテーションが関係する非定常現象の問題が顕在化してきた。

本論文は、H-2A ロケット LE-7A エンジン液体水素ポンプインデューサに発生したインデューサの非定常不安定現象の解明とこの抑制のための改良について示したものであり、全編6章よりなる。

第1章は緒論である。

第2章では、初期設計のインデューサが LE-7A エンジン液体水素ターボポンプに重大な軸振動を発生させた非定常不安定現象の原因を明らかにしている。すなわち、インデューサ入口付近の強い逆流現象によりキャビテーションに対する熱力学的効果が著しく減少し、インデューサの揚程曲線は流量増加に対して正の勾配となり、この結果インデューサ入口部に旋回失速現象が発生し、これが過大な軸振動を発生させたことを明らかにした。この現象は高速の液体水素インデューサに特有なものであることから、これらの結果は、高速極低温流体機械の設計上極めて有用な成果である。

第3章では、LE-7A エンジン液体水素ターボポンプの初期設計インデューサに発生した旋回失速現象を抑制する改良設計について述べている。すなわち、改良設計では、旋回失速の主要な発生要因であるインデューサの入口部逆流の減少を目的として、インデューサの比速度を考慮して、インデューサの入口直径を小さくし（入口流量係数を大きくし）、出口直径を変更しない斜流形式のインデューサを選定した。この方式により、インデューサ揚程を変更せずに入口の逆流を大幅に抑え、旋回失速現象の抑止に成功した。したがって、液体水素ターボポンプに関しては、インデューサのみの設計変更で前記不安定現象を抑止するという極めて簡便な方法を見出したものであり、高速液体水素ターボポンプの設計に対して極めて重要な成果である。

第4章では、改良設計インデューサの性能について述べている。改良設計インデューサは、まずインデューサ単体で作動流体を水にした試験ならびに作動流体を液体水素として液体水素ターボポンプ単体試験を行い逆流の抑制、旋回失速や旋回キャビテーションなど、非定常不安定現象の発生の有無を調べた結果、旋回失速現象はロケット飛翔時の作動範囲において完全に抑制され、また水試験で発生した旋回キャビテーションは、液体水素の大きな圧縮性により抑制されることを明らかにした。これらの結果は、ターボ機械ならびに低温流体工学に新たな知見を与えた。

第5章では、LE-7A エンジン試験ならびに H-2A ロケット打ち上げ時における改良インデューサの性能を示している。エンジン試験においては、実機飛翔時で予想される入口圧力、流量、液体水素温度、回転数など広範囲の作動条件で試験が行なわれたが、液体水素ターボポンプ単体試験の性能が再現されるとともにその耐久性が確認された。また、これまでの6回の H-2A ロケット打ち上げにおいて改良インデューサは良好に作動した。これらの結果は、ロケット工学にたいして重要な技術資料を与える。

第6章は結論である。

以上要するに本論文は、LE-7A エンジン液体水素ターボポンプのインデューサに発生した液体水素特有の旋回失速現象の究明とこれを抑止するインデューサの改良について述べたものであり、航空宇宙工学ならびに低温流体工学の発展に寄与するところが少なくない。

よって，本論文は博士(工学)の学位論文として合格と認める。